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CHAPTER 20

BIOMASS USES AND CONVERSIONS

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I. INTRODUCTION

Corn, or maize, is produced mainly for food and feed from the grain or for use of the entire plant as silage. As described in preceding chapters, the grain also is processed to provide a host of industrial products. However, substantial portions of the plant remain unused or underused. This chapter discusses the underutilized coproducts, corncobs and stalk residues, and gives some potential uses. Production of the corn plant as a source of extractable sugars for fermentation and other applications is also discussed.

II. CORNCOB RESIDUE

For every 100 kg of corn grain, approximately 18 kg of corncob is produced. Thus during the past five years, the annual corncob production worldwide averaged about 70 million tonnes. In 1979, about 1.1 million tonnes of cobs were used industrially. Nearly 0.7 million tonnes were converted into furfural and 0.3 million tonnes were used as granular products (Foley and Vander Hooven, 1981). An additional 0.1 million tonnes filled a variety of industrial applications, including production of xylose. An undetermined amount is consumed as animal feed. At $35 per tonne, the 1979 world value for industrial cobs was $38.5 million. The value increase from processing has been estimated as fivefold, thus equaling nearly $190 million worldwide.

The corncob consists of four distinctly different parts—pith, a woody ring, coarse chaff (tough woodlike flakes), and light chaff (Fig. 1). By weight, pith makes up about 1.9% of the cob, the woody ring about 60.3%, coarse chaff about 33.7%, and fine chaff about 4.1% (Clark and Lathrop, 1953). The ring and coarse chaff are hard, woody, and resistant to abrasion and granulation. These characteristics were the basis for their early industrial applications (Lathrop, 1947).

Foley (1978) compiled a comprehensive review of the chemical and physical properties of corncobs and of their uses, including proprietary products of The Andersons (Maumee, OH). Selected properties are shown in Table I.

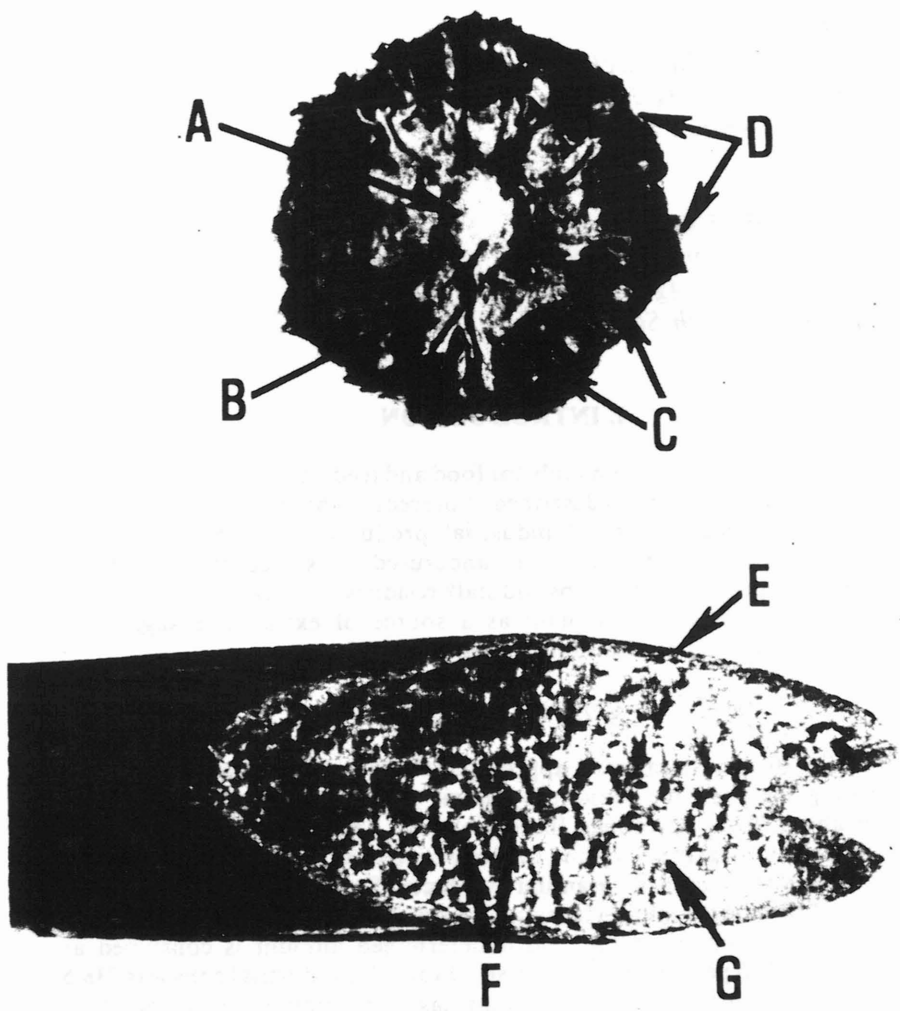

Fig. 1. Top: corncob cross section showing pith (A), woody ring (B), source of coarse chaff (C), and beeswing (D). Bottom: cornstalk cross section showing cortex (E), vascular fibrous bundles (F), and pith (G).

A. Cob Collection

Before the introduction of the picker-sheller and corn combine, cob collection accompanied grain harvest. Hudson (1984) discussed an industrial corncob refining operation. He reported that good weather and abundant harvest generally assured adequate supplies of cobs. However, if the corn price is high, the farmer becomes more interested in dealing with the grain. Collecting crop residues interferes with timely harvest of the commodity with the highest value. Thus, cobs and other crop residues must have value sufficient to pay their way before an enduring market can develop. Many researchers have tested collection procedures for retrieving cobs directly from the combine, either with the grain or separately.

Because hybrid corn seed is harvested with the cob, this unique operation offers the opportunity for cob utilization. Cobs have been used by a commercial seed producer as an alternative source of energy for drying seed corn (Peart et al, 1981). Claar et al (1981) report that, based on an energy and economic analysis, corncobs are a better fuel source than stover.

Because corncobs are available for only a short time, year-around supply necessitates storage. Dunning et al (1948) reviewed corncob-storage studies reported by grinding industries in the Midwest using various indoor and outdoor techniques. Representative samples removed from storage at 6-in. intervals, starting at the top of the pile and continuing to a depth of 42 in., were evaluated for contents of moisture, pentosan, and cellulose. Cobs stored indoors, with adequate ventilation, equilibrated at about 15% moisture and showed no change in composition during the initial five months. Pentosan and cellulose loss during outdoor storage was insignificant during the initial six months, but losses of both pentosan and cellulose were appreciable after 12 months of outdoor storage. Similarly, Smith et al (1985) evaluated material from commercial cob piles (1,000–2,000 t) stored outside for six and 18 months. Also, they studied smaller corncob piles (3–18 t) stored outside for 6, 9, and 18 months. The greatest loss of dry matter and available energy occurred in the outer 3 ft. The interior cobs from the large commercial piles did not deteriorate

TABLE I
Selected Chemical and Physical Properties of Corncob Fractions[a]

		Fractions	
Property	**Whole Cob**	**Woody**	**Pith/Chaff**
Cellulose, %	41.2	47.1	35.7
Hemicellulose, %	36.0	37.3	37.0
As pentosan, %	(34.6)	(36.5)	(34.7)
As xylan, %	(30.0)	(31.6)	(30.1)
Pectins, %	3.1	3.2	3.2
Lignin, %	6.1	6.8	5.4
Gross energy, Kcal/kg	3,998	4,113	4,157
Absorption[b]			
Oil, %	259	100	500
Oil (water-saturated cob), %	259	100	500
Water, %	369	133	727
Water (oil-soaked cob), %	208	75	409

[a]Source: Foley and Vander Hooven (1981); used by permission.
[b]Liquid absorbed as weight percent of dry corncob absorbing material.

significantly when moisture content remained below 12%. However, deterioration was appreciable when moisture content exceeded 20%. For example, 43% of the pentosan and 36% of the cellulose were lost after 18 months. Thus, corncobs are best stored with some appropriate shelter or in large, tall piles where the top 3–4 ft are considered protective cover.

B. Processing, Conversion, and Uses

As mentioned previously, the unique properties of cobs provide for many industrial uses. Most require grinding or milling. Much initial corncob processing research was conducted at the Northern Regional Research Center (Clark and Lathrop, 1952). The least complex grinding operations are for producing cattle feeds, mulch, and litter. Hammer-mill grinding usually satisfies the requirements, but screening to size and content for more efficient uses is recommended. To meet requirements for the myriad of uses, many techniques have been developed. Foley and Vander Hooven (1981) reported that the present practice involves a series of crushers and hammer mills, subsequent drying to 10% moisture or lower, and further size reduction by attrition or roller mills. Segregation and classification are then achieved by a variety of screening configurations and sieve sizes. To avoid machinery damage, attention must be given to the removal of stones, tramp metal, and other such materials. Throughout the milling, cobs are aspirated to separate pith and chaff from the woody portion. Special attention must be taken to avoid dust explosions and fires while these dry, finely divided, charged materials are being processed.

Clark and Lathrop (1953) summarized many initial uses for processed cobs. Early demands were for use as animal and poultry bedding, as mulches and soil conditioners, and fiber and roughage in animal feeds. Pith fractions provide an exceptional carrier of micronutrients in animal feed. Corncobs have served as a useful component of composts for growing mushrooms (Foley and Vander Hooven, 1981). Because of the absorption properties of corncob, fractions of suitable particle size have served as effective carriers of insecticides and other agricultural chemicals. Corncobs have served as fillers in many industrial applications (e.g., adhesives, roofing materials, caulking compounds, explosives, and plastics).

Because of the exceptional hardness of woody ring particles, corncobs have been widely used as material for finishing milled metal parts, plastics, hard rubber products, and glassware. During World War II, many ordnance materials were polished, deburred, and cleaned with ground corncobs. Ground cobs are used as scrubbing agents in powdered handsoaps, and cob fractions are used in the cleaning and dressing of furs and pelts (Clark and Ashbrook, 1953).

Most uses described above depend on the mechanical and physical characteristics of corncobs. However, corncobs are a major source of furfural (McKillip and Sherman, 1980). This aldehyde-substituted furan is readily produced by acid hydrolysis of the pentosans contained in corncobs, oat hulls, and other crop residues. The resulting pentose sugars are dehydrated during continued heating in the presence of strong mineral acids, such as sulfuric acid. The furfural is steam-distilled and collected for direct use or conversion to other chemicals. Those of significant commerce are the hydrogenated products, tetrahydrofuran and tetrahydrofurfuryl alcohol. Furfural serves as an intermediate for the manufacture of various other industrial chemicals, including hexamethylenediamine (used in the production of nylons). Tetrahydrofurfuryl nitrate as a 7–8% blend with ethanol has been substituted for diesel fuel in Brazil (Anonymous, 1983).

Corncobs could be fractionated into their major chemical constituents (cellulose, hemicellulose, and lignin) as well as their minor constituents. However, recent interest has emphasized the prior technology for conversion of the polysaccharides to their constituent simple sugars, mostly glucose and xylose (Dunning and Lathrop, 1945). These sugars can serve their usual market, including energy and carbon sources for fermentation media.

III. STALK RESIDUE

Corn harvest, worldwide, averaged 127 million hectares annually from 1979 through 1983. A conservative estimate for stalk residue of 1.5 t ha^{-1} indicates that 190 million tonnes were available for possible use. At $30/t, the world market for stalk residue was $5.7 billion. However, good soil and water management practices require that some crop residue be returned to the soil and hence dictate practical limits for collection (Larson, 1979). Further, existing technologies for industrial utilization of stalk residue are not sufficiently competitive in most economies to establish a sustained market.

Cornstalks consist of an outer cortex (containing fiber bundles) and vascular fibrous bundles surrounded by pith (parenchyma tissue) (Fig. 1). The pith contributes nearly 25% of the total dry stalk weight (Whittemore et al, 1935). Analyses for major chemical constituents of the different stalk fractions reveal only small differences. Selected, representative data are shown in Table II. Schultz et al (1984) and Sloneker (1976) reported cornstalk cellulose contents of 35 and 29.3%, respectively, and glucose contents, available after acid hydrolysis of stalk samples, of 40.2 and 37.7%, respectively. These glucose values are in reasonable agreement with the cellulose data; however, the glucose values

TABLE II
Selected Chemical Characteristics of Cornstalks at Harvest

Characteristics	Whole Stalk	Cortex	Vascular Bundles	Pith
Glucose,[a] %	38[b] (40)[c]	21[d]	21[d]	27[d]
Galactose, %	1[b] (NR)[c]	21[d]	21[d]	27[d]
Mannose, %	1[b] (3)[c]	1[d]	1[d]	1[d]
Xylose, %	16[b] (17)[c]	23[d]	21[d]	18[d]
Arabinose, %	2[b] (3)[c]	1[d]	1[d]	1[d]
Total sugar, %[a]	56.8[b] (NR)[c]	67.1[d]	65.3[d]	73.7[d]
Cellulose, %	38.4[e]	39.3[e]	37.1[e]	37.9[e]
Pentosan, %	27.6[e]	25.9[e]	26.4[e]	27.7[e]
Lignin, %	34.3[e]	24.2[d]	22.7[d]	14.6[d]
		(33.5)[e]	(35.2)[e]	(32.0)[e]

[a] Sugars of polysaccharide constituents analyzed following hydrolysis.
[b] Sloneker (1976).
[c] Schultz et al (1984); NR = not reported.
[d] McGovern (1982); monosaccharides adjusted to basis sugar.
[e] Webber (1929).

reported by McGovern (1982) are in poor agreement with the cellulose data. The data reported (Table II) for arabinose, xylose, and mannose are in close agreement; however, the galactose values are significantly different. The glucose and galactose data need further attention. Although it may be fortuitous, the sum of the two values reported by McGovern is in close agreement with cellulose data. McGovern (1982) commented on the low glucose and high galactose values obtained for his Wisconsin-produced corn but offered no explanation. None of the researchers reported fructose; however, low levels could have been present.

Lignin data reported by Schultz et al (1984) and Sloneker (1976), 21.2 and 3.1%, respectively, and the data in Table II are rather diverse. The range of values may result from differences in methods of hydrolysis and analysis and from differences among varieties, relative maturity at harvest, harvest date, and associated rainwater leaching. For comparison, consider the effect of maturity and field storage on the chemical composition of kenaf (Clark et al, 1967; Bagby et al, 1975). As the plants matured, structural carbohydrates and lignin contents increased, with corresponding declines in soluble substances. Similarly, during the two months standing in the field following a killing frost, soluble constituents decreased and relative percentages of cellulose, hemicellulose, and lignin increased (Bagby et al, 1975).

A. Stalk Collection and Storage

Cornstalk residue may be baled, cubed, stacked loose, chopped, or bundled and stored indoors or outdoors. Numerous approaches were discussed over 50 years ago (Sweeney and Arnold, 1930). Even more techniques are available today. Large balers and mechanical stackers, developed for silage and hay, are available to pick up plant residue directly from the field for transport to processing or storage sites (Richey et al, 1982). However, only about one half of the available residue is readily collected.

Because of low bulk density, handling can be improved by compression into bales, cubes, or pellets. End use, storage, and transportation needs may determine the most effective package. Miles and Miles (1980) state that if truck transport and storage are the determining factors, there is no need to exceed 16 lb/ft_3 (256 kg m^{-3}), because that density results in reaching the limits for both volume and weight.

As for all crop residues, year-around processing requires appropriate storage. The method for storage depends on how the material will be used and into what form it is packaged. Heid (1984) reported that storing crop residues outdoors may result in losses of 5–50%. Covered or indoor storage resulted in about a 5% loss during six months. However, that experience is mainly with relatively small stacks or large bales stored in single tiers. Sloneker (1976) noted that spoilage is greater if stacks or large bales are allowed to touch one another during outdoor storage. Large-scale use of stalk residue would probably require stacking to minimize storage area. No doubt further storage tests are necessary.

B. Processing, Conversion, and Uses

More than 50 years ago, Arnold (1933) listed 60 products from cornstalks, cornhusks, and cornstalk pith ranging from fodder to chemicals and materials such as α-cellulose, furfural, oxalic acid, paper, wall board, and door mats. In the late 1920s, an insulating-board mill at Dubuque, Iowa, used cornstalks as a raw material before switching to more economical materials. In 1927, the Cornstalks Products Company, Danville, Illinois, started production of cornstalk paper pulp (Wells and Steller, 1943). That mill produced about 45 t per day of pulp, but after a few years, it discontinued production for economic reasons associated largely with problems of continued supply and preservation of cornstalks. The pulp was used in blends with other fibers to form various grades of paper of acceptable market quality. In the later 1950s, the Israelis were partially successful in collecting and pulping cornstalks (Tall, 1959). However, this venture proved too expensive for continued operation. As with sugarcane bagasse, efficient pith removal improves the properties of the pulp and the efficiency of pulping chemicals.

Building panels from cornstalks were developed by Lewis et al (1960). The waxy coating on cornstalks interfered with resin bonding; however, flaming the stalks burned off the wax to provide a readily bonded surface. Although the panels were not of high strength, Lewis and co-workers concluded that their panels were sufficiently strong to use in one and two-story buildings without additional framing support. This technology has received little industrial attention.

Cornstalks have been processed to dissolving pulps in excess of 95% purity (Abou-State et al, 1983) by a process involving prehydrolysis hydration for 1 hr in boiling water. Subsequent hydrolysis with 0.75% sulfuric acid for 6 hr at 100° C and a 20:1 liquid-to-solids ratio followed by alkaline pulping using kraft, soda, or sulfite conditions for 5 hr at 100° C produced a satisfactory dissolving pulp. The degree of polymerization (970–1,140) compared favorably with commercial dissolving pulps from sugarcane bagasse and softwood having degrees of polymerization of 920 and 860, respectively. The residual pentosan contents ranged from 4.0 to 5.1%, a level similar to that of the commercial bagasse pulp (4.5%) but somewhat greater than that of the softwood pulp (3.2%).

As stated above, cornstalks are used as animal feed; however, low digestibility limits intake and nutritive benefit. Although ruminants possess the hydrolytic means to convert structural polysaccharides (i.e., cellulose and hemicellulose) to readily metabolized sugars, the encapsulating effect of lignin covering the fibers and polysaccharides is believed to limit their conversion. Other interrelated and limiting characteristics include cellulose crystallinity, hydrogen bonding, limited available surface area, and low hydration. The feed value of cornstalks has been improved by treatments known to diminish the above characteristics. For example, Oji et al (1977) reported results from several alkaline treatments (2% sodium hydroxide plus 2% calcium hydroxide, 3% ammonia, and 5% ammonia). Effects of these treatments were evaluated in feeding tests with eight wether lambs. Organic matter intakes increased by 45–51%, and gross energy digestibility improved by 12–14% in comparison with the control.

Various chemical and physical treatments have been applied to improve the susceptibility of lignocellulosics, such as cornstalks, to enzymatic conversion (Duckworth and Thompson, 1983; Ladisch et al, 1983). Renewed interest during recent years has focused on production of the constituent sugars and their subsequent fermentation to ethanol and other chemicals. As for corncob conversion, acid hydrolysis techniques also have been investigated extensively for the conversion of cornstalks to their constituent sugars (Dunning and Lathrop, 1945; Bhandari et al, 1984).

IV. SUGAR AND ETHANOL FROM THE CORN PLANT

The stalk portion of the corn plant has the capacity to store considerable energy. Stalk solids consist mainly of carbohydrates. Cellulose, hemicellulose, and soluble sugars are the major constituents of the mature plant. Other compounds include pectic substances, other soluble solids, insoluble lignin, and cutin (wax).

Limited consideration has been given to systems that utilize the entire corn plant. An example is the use of the whole plant for ruminant animal feed as fodder or ensilage, converting plant bulk to a more storable form. Annual worldwide silage production averaged 103.9 million tonnes during 1974–1983. Development of additional systems for single or multiple-use purposes may be useful to maximize the profitability of the crop, as well as to determine its ability to compete with other crops. Sugar production from high stalk-sugar varieties is one such possibility.

A. Background—Cornstalk Juice Sugar

Cornstalks have been considered a source of sugar for almost as long as the grain has been used in modern times. Blackshaw (1912) stated that sugar in the juice of cornstalks was known in the 1500s and that molasses was made from the juice in America during the 1700s. He noted that renewed interest in the manufacture of sugar from the juice of cornstalks resulted from a paper presented to the Linnean Society in 1843 by Prof. Croft. In 1850, a factory was established in France for sugar production from cornstalk juice, but it could not compete with the beet sugar industry.

Sucrose purity in soluble solids of cornstalk juice is lower than that of beets and cane, often resulting in poor crystallization. Collier (1884) recognized cornstalks as a promising source for sugar but viewed them as inferior to sorghum. Blackshaw's results (1913) on juice quantity and quality were similar to those of Collier, as were the findings of Clark (1913), but they stated that corn compared very favorably with sorghum as a sugar-producing plant. Stewart (1906, 1912) patented processes for making cornstalk sugar, even though he focused mainly on complete utilization of the plant for simultaneous production of sugar, cellulose, and alcohol.

Cornstalk juice for syrup production apparently was largely ignored by early investigators, although it was mentioned briefly by some. A detailed study of this alternative, using sweet-corn stalks, was begun in 1921 by the University of Minnesota in cooperation with the Minnesota State Canners' Association. This effort (Willaman et al, 1924) did not result in optimism about the development of a syrup-making operation in conjunction with the sweet-corn canning industry. All commercial corn syrups and sweeteners have been produced by hydrolysis of starch obtained from corn grain by the wet-milling industry beginning in the mid-1800s (Chapter 17). Stalk juice for making syrup has never been a competitive option, although sorghum syrup has been widely produced in many U.S. rural communities, including those of modern-day Amish farmers.

The carbohydrate content of the stalk juices from sweet-corn plants after harvest of the ears was reported by Gore (1947) in terms of alcohol yields. The estimated yields, all less than 950 L ha^{-1} (100 gal/acre), were comparable to conversion of approximately 2.5 t ha^{-1} (40 bu/acre) of grain yields at a conversion rate of 400 L of ethanol per tonne of grain. D'Ayala Valva et al (1980) estimated alcohol yields to be twice as large (2,000 L ha^{-1}) from juice sugar of dent hybrid cornstalks. Yields of this magnitude compare favorably with those of sweet sorghum, an unexpected result, considering that corn hybrids were developed for grain yield rather than for stalk sugar.

The energy crisis of the early 1970s stimulated renewed interest in the evaluation of corn as a carbohydrate source in the production of ethanol for fuel. Most interest centered around use of grain because the technology was already well developed. However, the sugar content of succulent green stalks of corn and other crops was investigated to determine its production and process efficiency for conversion to ethanol.

Inbred C103, identified by Singleton (1948) as having high stalk-sugar content, was suggested for use in silage hybrids to improve the feeding value. Smith (1963) later concluded that corns with high stalk sugar have no superiority over conventional corns in silage production, because free sugars are not found to improve silage palatability. Collings et al (1979) confirmed that soluble sugars decrease to less than 1% during the first 13 days of ensilage. Hybrids developed from Singleton's material (1948) were incorporated into the high-stalk-sugar corn developed by Blanco et al (1957). Cunningham et al (1980) found these lines to have stalk sugar contents (oven-dry basis) of 30–34%, about two to three and a half times greater than those of standard varieties. Blanco and co-workers developed their hybrids for the multiple purpose of producing grain and stalk products.

B. Plant-Sugar Relationships

The sugar contents of cornstalks have frequently been measured as a function of their relationship to other important agronomic traits. DeTurk et al (1939) reported that stalk sugars provided some protection against cold injury and proposed that this was probably attributable to a lowering of the freezing point of plant tissues. They also reported increased resistance to fungal attack by those plants having the highest stalk-sugar levels. A more detailed study by Craig and Hooker (1961) substantiated this early observation and also attributed senescence of pith tissue to low levels of sugar.

Sugar content in the normal cornstalk generally increases steadily throughout the life of the plant until the middle to late stages of the grain-filling period. At five to six weeks after pollination, depending on the hybrid, stalk-sugar content decreases substantially as carbohydrate reserves are transferred to the ear sink (Welton et al, 1930; Van Reen and Singleton, 1952). Stalk-sugar accumulation was reduced when leaves were removed during any stage of plant growth (Asanuma et al, 1967), but removal of ears or prevention of pollination had the opposite effect. Increases of 30–50% in sugar content or percent soluble solids occur in the stalks when plants are detasseled to prevent grain formation (Ertugrul et al, 1964), when earshoots are covered to prevent pollination (Sayre et al, 1931), or when plants are barren (Hume and Campbell, 1972). Male sterility, detasseling, or some other method of seed-development suppression is necessary if the intent is to harvest the stalks for the juice sugars alone. However, harvesting the corn plant for a single carbohydrate product may not be the best way to maximize yields.

Sugar concentration in the stalk tends to increase from the base (Welton et al, 1930; Van Reen and Singleton, 1952). Although the percentage of sugar in the juice increases from the base toward the top of the stalk, the total sugar content decreases because of the relative sizes and juice contents of the internodes. A typical distribution of soluble solids ranging from 13–16% in various internodes of more recently developed hybrids is shown in Fig. 2. One notable deviation from the findings of previous authors is the higher concentration of soluble solids in the two basal internodes in comparison to those higher on the stalk, near the ear. This increase might be attributable to recent selection to increase stalk rot resistance, a character known to correlate with sugar content. Such changes in sugar content are certainly not unique, in view of the success of Blanco et al (1957) in changing stalk sugar contents through selection. Van Reen and Singleton (1952) concluded that variable stalk-sugar contents found among dent inbreds could not be accounted for by differences due to grain production alone. More recent evaluations of hybrids and other cultivars (Widstrom et al, 1984) confirm that the available variation among genetic types is large enough to facilitate substantial progress in selection for high sugar in the stalks.

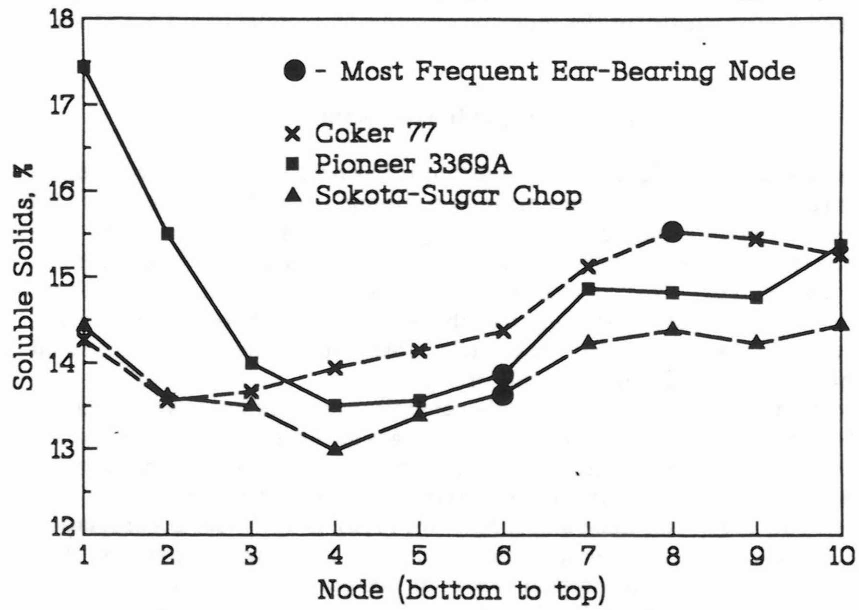

Fig. 2. Soluble solids (%) in cornstalk juice expressed six weeks after pollination from the bottom 10 nodes of three hybrids grown in 1981, 1982, and 1983. Each data point is the average of 180 individual samples.

C. Measurements for Comparisons

The sugar industry has developed various methods for determining sugar content or yield of plant juices. These methods usually give values for percent soluble solids, which are measured with a refractometer when quick relative values are desired. For more accurate measurement of sugars or of sucrose alone, polarimeter readings are used. For cornstalks, as for sugar cane, sugar contents of expressed or extracted juices may be readily determined using a refractometer for most breeding and field evaluation purposes (Betterton and Pappelis, 1964; Campbell and Hume, 1970). Refractometric readings measure percent soluble solids and are convertible to total sugar contents by referring to tables correlating sugar content and refractometer values.

Problems are encountered when comparisons are attempted among different crops. D'Ayala Valva et al (1980) suggested that easy comparisons could be made between cornstalks and sugarcane because the same processing facilities can be used for both to produce sugar, syrup, or alcohol. However, crops differ in their production requirements. For example, University of Michigan researchers have shown that corn silage and sugar beets require about the same production energy inputs, whereas potatoes require five to six times as much energy as either (Myers et al, 1981). Even the same crop may have varying requirements in terms of its output-input energy ratio. For corn produced in Mexico, this ratio can vary from 4.25 to 128.2, depending on whether corn grain is produced by hand-power or by the use of oxen (Pimentel and Burgess, 1980). The same ratio varies from 0.78 to 4.21 for irrigated corn in the United States. A similar energy analysis of sugarcane for alcohol production gave ratios ranging from 0.9 to 1.8, depending on whether crop residues or fossil fuels were used for processing energy (Hopkinson and Day, 1980). Regardless of the method used for comparing crops, most people devising systems now recognize the need for considering multiple uses, as did Blanco et al (1957). People have more awareness now of the need to consider all production opportunities that will eventually decrease the cost of energy delivered to the consumer (Lipinsky, 1978a), including conversion of the crop to ethanol.

D. Corn Compared with Other Crops as Ethanol Sources

The technology that will allow crop comparisons to be made on the basis of total carbohydrate production, reduced to yields of sugar or ethanol, will require improved processes for enzymatic hydrolysis of cellulose (Spano et al, 1980). A uniform system is needed to make easy comparisons among crops with high carbohydrate production potential such as pearl millet (Rao et al, 1982), sweet sorghum (Broadhead et al, 1978), sugarcane (Lipinsky, 1978b), and sugar beets and corn (Hills et al, 1981). Other crops like potatoes and Jerusalem artichoke, could be added to the list when production of total carbohydrates is considered. Some complex selection practices, such as those used for evaluating sugarcane varieties (Punia et al, 1982), could also be greatly simplified if the quantity of carbohydrate or energy measurement, rather than quality, received the main emphasis.

Breeding for high sugar production in the stalks of corn is an attainable goal (Widstrom et al, 1984). If that were done, cornstalks could be integrated into the existing processing systems for sugarcane and sugar beets, as suggested for sweet sorghum by Lipinsky et al (1979). Corn compares favorably with other crops in producing fermentable sugars or alcohol, even when only the grain production is considered (Hills et al, 1981, 1983) and has resulted in a large fuel ethanol industry in the United States (Chapter 19). Grain yields in the study by Hills et al (1981) were high at approximately 250 bu/acre (ethanol, 609 gal/acre) but were achievable under intensive cultural conditions and high energy input. The ethanol yield for corn grain was 74% of that for sugar beets and nearly equal to that of sweet sorghum. Work at Tifton, Georgia, indicates (Table III) that at grain yields of about 8 t ha^{-1} (about 300 bu per acre) at six weeks after pollination, over 40% additional ethanol yield can be added because of the remaining soluble sugar contributed by the stalk. Comparisons were made in ethanol yields per plant to provide a common denominator for combining stalk-sugar and grain production.

Additional factors must be considered if valid comparisons among crops are to be made. First, the adaptability of the crop to a wide growing area is an important consideration. Sugar beets and sugarcane both have a somewhat limited growing region in the United States, whereas corn and sorghum are widely grown and have a broad area of adaptation. In fact, two crops of corn can be grown per year over a rather wide area of the southeastern United States (Widstrom and Young, 1980). Although grain yields of a second crop are less than those of the first crop, dry-matter or stalk yields are large enough to make it a respectable forage option.

The length of time for a crop to mature for optimum carbohydrate production is another important consideration. This provision allows any crop to be compared with another on the basis of carbohydrate yield per unit area per unit time. Blanco and Blanco (1960) showed a substantial advantage for corn over sugar beets using this method. When adjusted to a net energy value (net energy equals total energy yield minus energy used in production) and to the same units of area and time, appropriate assessments of the crops can be made. Table IV illustrates the great differences among several crops in the time required for production. Its wide adaptation, short growing season, and the many options available for its use make corn a strong competitor with any crop when

TABLE III
Total Sugar and Starch Production (Reported as Potential Alcohol) of Stalks and Grain of Three Hybrids Grown in Georgia for Three Years and Harvested by Four Procedures

Hybrid	Ethanol Yields (ml/plant) of Harvesting Procedures[a] Method 1	Method 2	Method 3	Method 4	Mean[b]
Coker 77	41	38	66	65	53 a
Pioneer 3369A	33	27	67	65	48 b
Sokota Sugar Chop	24	21	62	57	41 c
Mean[b]	33 y	29 z	65 x	63 x	

[a] Methods 1 and 2: harvest at six weeks postpollination of stalks for juice after covering ear (Method 1) or removing ear (Method 2) to prevent pollination. Method 3: simultaneous harvest at six weeks postpollination of grain and juice of pollinated plant. Method 4: harvest of mature grain (30% H_2O) at approximately six weeks postpollination and subsequent harvest of stalk juice two weeks later.
[b] Marginal means not followed by the same letter are significantly different at the 1% level of probability.

compared in terms of net energy produced per unit area over a specified length of time. This is apparently one reason why corn has become a dominant carbohydrate-producing crop in temperate climates.

V. SUMMARY

Corncobs satisfy numerous industrial applications, which result in the domestic processing of over a million tonnes annually. Furfural production consumes nearly 70% of the processed cobs, and granular products provide the next largest market. Since introduction of the picker-sheller and corn combine, corncobs are less readily available, and the grain no longer must support the collection and disposal of the cob. Consequently, corncob products must bear the cost of their separate collection, storage, and conversion before an enduring market can develop.

Cornstalk residues have been evaluated for a variety of products and have enjoyed short-term industrial markets as fiber resources for pulp, paper, and board products. However, the stalk residue was not economically competitive with other fiber resources. Techniques to improve digestibility and nutritional value of cornstalks are of continuing interest. Because of the recent petroleum shortages and the approaching petroleum dearth, renewed interest has emerged in the conversion of cornstalks to industrial feedstocks and chemicals through sugar production.

Cornstalk juices have been used to make molasses and other sweeteners since the 1700s. Cornstalk sugar has lower purity than that of sugarcane or sugar beets and is therefore used to make syrup. The sugar content of cornstalks can average as high as 30%, with the percentage increasing from the lower nodes toward the top. Some corns are much higher in stalk sugar than others, a trait that can be further increased because it is highly heritable.

Interest in maize as an energy-producing crop was renewed during the 1970s because of the energy crisis. For purposes of energy comparisons among crops, total carbohydrate production is an effective comparative measure. The comparisons should be based on net energy, with due regard for efficiency, and should also take into consideration the land area needed and the time required for production. Crops should be evaluated on a systems basis, that is, production options and versatility of product uses are important to maintain. Corn is very competitive as a high carbohydrate-yielding plant species when one considers 1) the short growing season it requires (two crops per year in many areas), 2) the multiple options available for its uses, 3) its broad area of adaptation, and 4) its efficient photosynthetic production of usable energy.

TABLE IV
Length of Growing Season and Area of Adaptation for Several High Energy-Producing Crops

Crop	Length of Growing Season (mo)	Area of Adaptation in the United States
Corn	3–4	General
Sugar beets	At least 6	North
Sugarcane	12	Extreme south
Sweet sorghum	4–5½	South and central

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